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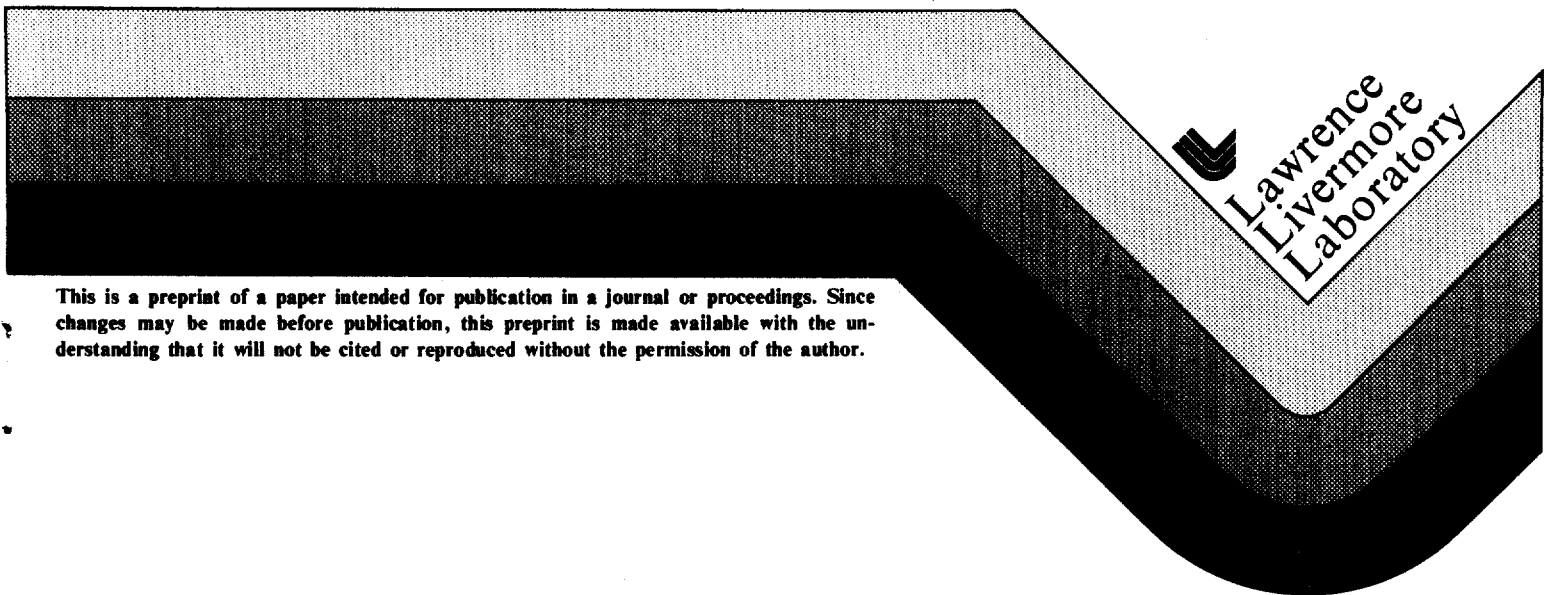
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## Theoretical View of the Plasma Focus

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### Abstract

The present theory of the plasma focus device is discussed. Experiments at low pressure clearly show a disruption of the current sheath and the formation of energetic electron and ion beams in a turbulent medium. Possible directions for calculations to explain this conversion of magnetic energy into charged particle beams are indicated.

### 1. Two-Dimensional Magnetohydrodynamic (2-D MHD) Model

The plasma focus is a type of magnetic shock tube which can be idealized as a cylindrically symmetric device consisting of a central anode surrounded by a cathode. The space between the two electrodes is filled with several Torr of deuterium. This "gun" is connected to a capacitor bank or an explosive generator. Referring to Fig. 1, we take the breakdown path to be in the radial direction, across the face of the insulator. A magnetic field  $B_0$ , due to the current, accelerates the current sheath in the axial direction. The motion of this sheath sends a shock front into the gas and leaves a vacuum region behind it, filled with magnetic field. The configuration of the shocked gas is shown in Fig. 1. Radial flow through the cathode must be taken into

account because typical cathodes consist of a set of bars surrounding the anode.

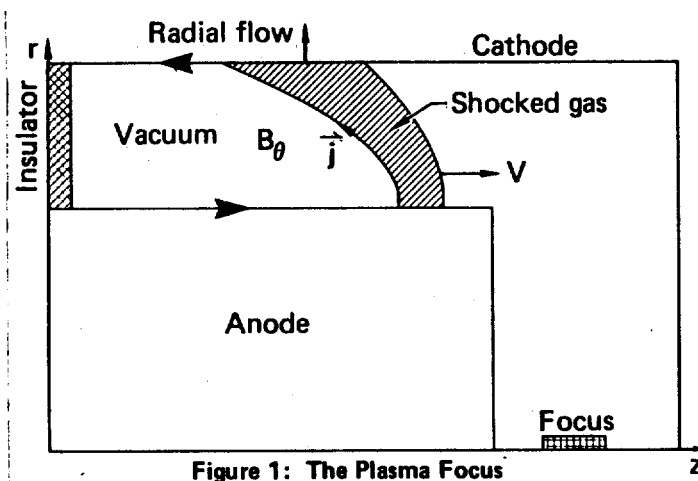


Figure 1: The Plasma Focus

When the current sheath reaches the end of the anode, an axial component  $j_z$  develops in the gas so that there is a collapse of the sheath toward the axis. Typical times are a few  $\mu\text{sec}$  for the rundown and a few hundred  $\text{nsec}$  for the collapse.

The shock is then "focused" on axis,  $\sim 2\text{cm}$  in front of the face of the anode, as shown in Fig. 1. The size of the "focus" is  $\sim 2.5$  in length and  $\sim 2\text{mm}$  in radius, moving with a velocity 50-100  $\text{cm}/\mu\text{sec}$  along the axis, away from the anode.

Two-dimensional MHD calculations have been performed for the plasma focus.<sup>1</sup> The full MHD equations are solved in cylindrical symmetry using initial values consistent with the initial breakdown path in the gas.

Typical values for the plasma parameters are  $\eta$ (compression)  $\sim 4$ ,  $kT \sim 15\text{eV}$ ,  $V_z \sim 8\text{cm}/\mu\text{sec}$ ,  $B_\theta(r=5\text{cm}) \sim 40\text{kG}$  for the rundown, and  $\eta \sim 35$ ,  $kT_i \sim 1\text{keV}$ ,  $V_z \sim 60\text{cm}/\mu\text{sec}$ , and  $B_\theta(r < 3\text{mm}) \sim 400\text{kG}$  for the "focus." According to the 2D-MHD calculations, the thickness of the shocked region is  $\sim 1.5\text{cm}$  and the thickness of the current sheath is  $\sim 6\text{mm}$ , just above the anode.

Agreement between experiment and calculations for the current trace is not difficult to obtain because the inductance of the capacitor bank dominates until late times. To test the MHD model, detailed measurements of the plasma parameters must be made and compared with calculations. This has not yet been done.

When the shock reaches the axis, a high pressure region is formed which expands outward against the incoming current sheath. The resulting deceleration of the sheath can be seen on the  $\frac{dI}{dt}$  trace. Finally, plasma flow along the axis relieves the high pressure and the current sheath continues its motion toward the axis. The neutron yield and hard X-ray yield is obtained when the current sheath breaks up due to instabilities.

## 2. Experimental Situation

A series of experiments has been carried out by Vladimir Gribkov and his colleagues at the Lebedev Institute in Moscow. Extensive diagnostics (laser interferometry, etc.) show a violent disruption of the current sheath at radii 1mm-1cm. This is followed by formation of an electron beam which deposits its energy on the face of the anode.

Another series of experiments, carried out by Alain Bernard and his colleagues at Limeil using magnetic probes and ruby laser scattering, found that most of the current is carried in a thick ( $\sim 2$ cm) low density, turbulent region behind a thin, luminous sheath. Electron and ion beams were also studied in this work.

## 3. Non MHD Behavior

It is clear from the times associated with the disruption of the current sheath that instabilities at  $\omega \sim \omega_{pi}$ , where  $\omega_{pi}$  is

the ion plasma frequency, are playing an important role. We assume that, following shock thermalization in the region of the "focus" and rapid plasma flow out of this region in the axial direction, we are left with a low density, hot plasma which is collisionless. For example, if  $n = 10^{16} \text{ cm}^{-3}$  then  $\tau_e = 2\pi/\omega_{pe} = 1.1 \text{ psec}$  and  $\tau_i = 66.4 \text{ psec}$ . A disruption time of 1 nsec would be  $15 \tau_i$ . At a temperature of 10 keV,  $\lambda_D = 7.5 \times 10^{-3} \text{ mm}$ . Typical spatial widths for collisionless structures such as ion acoustic solitons would be  $70 \lambda_D = 0.15 \text{ mm}$ .

Clearly we need to have a fluid approach where microscopic instabilities are averaged over to give contributions to the momentum and energy equations.<sup>2</sup> The treatment of the instabilities can be tested on a simulation code.

The object of the non-MHD theory is to calculate the conversion of magnetic energy into charged particle beams when the current sheath disrupts. In order to study the initial phase of the breakup of the current sheath, an instability analysis of a collisionless current sheath is now being undertaken. Growth rates in both the r-z and r- $\theta$  plane are being calculated. Once a geometric picture is developed for the disruption, the fluid approach will be used to calculate the detailed behavior of the system.

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#### References

1. S. Maxon and J. Eddleman, Phys. Fluids 21, 1856 (1978).
2. See, for example, P. C. Liewer and N. A. Krall, Phys. Fluids 16, 1953 (1973).